

τ PHYSICS AT B -FACTORIES

Olga Igonkina

Physics Department, University of Oregon, Eugene, Oregon 97403, USA

Today the B -factories BaBar and Belle have accumulated largest samples of $\tau^+\tau^-$ events and are competing to be called τ -factories. Among the problems to be tested and measurements to be done by BaBar and Belle are check of CP and CPT invariance in tau decays, measurement of strange and non-strange spectral functions, extraction of mass of strange quark and $|V_{us}|$, searches for lepton flavor violation processes. In this paper, the latest results in tau physics by these two experiments and measurements to be done within next few years are reviewed.

I. INTRODUCTION

BaBar[1] and Belle[2] are the e^+e^- collider experiments running at \sqrt{s} equal to $\Upsilon(4S)$ mass. In spite of their commonly used name B -factories they also provide largest and cleanest samples today for study of tau physics. Indeed, the cross-section of $e^+e^- \rightarrow \tau^+\tau^-$ ($\sigma_{\tau^+\tau^-}$) at this energy is 0.89 nb, of the same order as $B\bar{B}$ cross section at $\Upsilon(4S)$ and just a bit smaller than $\sigma_{\tau^+\tau^-}^{thr} \simeq 1.2$ nb at $\tau^+\tau^-$ production threshold[3].

The $\tau^+\tau^-$ event produced at $\Upsilon(4S)$ has very characteristic topology. The decay products of two taus are well separated in space, such that if space is split on two hemispheres with respect to the axis of the event thrust, the decay products of two taus are mostly contained within opposite hemispheres. From other side, the boost is not as large as at LEP experiments, and the tracks are well separated. As both BaBar and Belle are multipurpose spectrometers, the full particle identification of the event can be performed. Usually tau decays have one (1-prong) or three (3-prong) charged particles in the final state, therefore the multiplicity of the $\tau^+\tau^-$ events is relatively small. The typical backgrounds are radiative Bhabha and di-muon events which can be suppressed by vetoing leptons or high momentum tracks, and hadronic $q\bar{q}$ events which are more isotropic and have in average more neutral particles.

Currently, BaBar has recorded about $6 \cdot 10^8$ tau decays, and Belle has recorded about 10^9 tau decays with large part of the statistics used in the analyzes presented below. In section II, we review high precision measurements of tau mass and lifetime, which allow test of CPT invariance, and discuss perspectives of measuring CP-violation in tau decays. Section III is concentrated on the description of the measurements of the hadronic tau decays. In the section IV the searches of lepton flavor violation in tau decays are described and the conclusions are drawn in section V. The future perspectives and limitations of different measurements are discussed throughout the paper.

II. STANDARD MODEL TESTS

The basic tasks of the τ -factories are to measure mass m_τ and time of life τ_τ of tau lepton. Belle has recently presented a preliminary measurement of $m_\tau = (1776.71 \pm 0.25_{stat} \pm 0.62_{sys})$ MeV[5] using pseudo-mass technique pioneered by ARGUS[6]. The sample of 253 fb^{-1} was used. Although the measurement is dominated by systematic uncertainties, it is largely due to the size of the control samples, and therefore is likely to be improved with increased statistics. The sample is also used to probe the difference between m_{τ^+} and m_{τ^-} which is found to be negligible, $|m_{\tau^+} - m_{\tau^-}|/m_\tau < 5.0 \cdot 10^{-4}$ at 90% confidence level (CL). This number is statistically limited as most systematic uncertainties are canceled in the ratio.

At the same time BaBar has concentrated on the tau lifetime measurement. The flight distance transverse to the beam λ_T is measured and corrected by polar angle of 3-prong system (Θ_{3pr}) to calculate the total decay length $\lambda = \lambda_T / \sin \Theta_{3pr}$. The dependence on azimuthal angle ϕ ($\lambda(\phi)$) is fitted to minimize the systematic uncertainties due to alignment of the vertex detector. The preliminary result is $\tau_\tau = 289.40 \pm 0.91_{stat} \pm 0.90_{sys}$ fs[7]. It is in agreement with PDG value $\tau_\tau = 290.6 \pm 1.1$ fs[14] and is the most precise measurement up to date. 80 fb^{-1} were used in the analysis. As in case of m_τ measurement, the systematic uncertainty are partially limited by statistics of control samples and is likely to be improved with luminosity, although not more than by factor of two. The preliminary study

of τ_{τ^+} and τ_{τ^-} showed no difference $\tau_{\tau^-} - \tau_{\tau^+}/\tau_{\tau^-} + \tau_{\tau^+} = (0.12 \pm 0.32_{stat})\%$, where the systematic uncertainty is to be estimated but likely to be small.

Using the above numbers averaged with PDG values and leptonic branching fractions[14] of tau one can compare lepton charged current coupling constants:

$$\frac{g_e}{g_\mu} = \sqrt{\frac{B(\tau \rightarrow e\nu\nu)}{B(\tau \rightarrow \mu\nu\nu)} \frac{(1 + C_{\tau\mu})}{(1 + C_{\tau e})}} = 0.9997 \pm 0.0024 \quad (1)$$

$$\frac{g_\mu}{g_\tau} = \sqrt{\frac{(1 + C_{\tau e})}{(1 + C_{\mu e})} \frac{\tau_\tau}{\tau_\mu} \left(\frac{m_\tau}{m_\mu}\right)^5 \frac{1}{B(\tau \rightarrow e\nu\nu)}} = 0.9980 \pm 0.0022, \quad (2)$$

where $C_{\tau e} = -0.004$, $C_{\tau\mu} = -0.0313$ and $C_{\mu e} = -0.0044$ are radiative corrections. No significant deviation from SM is observed.

The subject which is still in *to do* list of both experiments is a search of CP -violation in tau decays. While no such CP -violation is expected in SM, other contribution, like e.g. charged Higgs exchange can result in non-negligible effect in angular and visible mass distributions of tau decay products due to interference of vector and scalar parts. CLEO has searched for such effect in the decays $\tau \rightarrow K_S^0 \pi \nu$ [8] and $\tau \rightarrow \pi \pi^0 \nu$ [9] with 13.3 fb^{-1} . While no signal was found, the CLEO collaboration has put limits on imaginary part of charged Higgs coupling of $-0.172 < Im(\Lambda) < 0.067$ from $\tau^- \rightarrow K_S^0 \pi^- \nu$ data assuming $K^*(1430)$ scalar contribution and $-0.046 < Im(\Lambda) < 0.022$ from $\tau \rightarrow \pi \pi^0 \nu$ for maximal scalar contribution. The limits are at 90% CL. The largest source of the uncertainty here is the size of the sample recorded. Given that B -factories have almost two orders of magnitude more data, it should be possible to improve CLEO result significantly. It is clear, however, that the understanding of the systematic uncertainty will require a careful work, in particular, study of possible charge asymmetry in the detector.

Of course, there are more SM tests to be performed, such as measurement of tau electric and anomalous magnetic dipole moments, Michael parameters, measurement of ν_τ helicity. However, it is unlikely, that either BaBar or Belle will be able to improve previous measurements soon.

III. STUDY OF HADRONIC TAU DECAYS

Due to simplicity of the SM tau decays involving W^- exchange, it is possible to study the hadronization process in details. All hadronic tau decays are of interest, starting from the most common 1-prong $\tau \rightarrow \pi \pi^0 \nu$ up to not yet observed 7-prong tau decay. The analysis of spectral function of $\pi \pi^0$ is to be used for comparing the measurement of anomalous magnetic moment of muon with SM prediction. The analysis of tau strange decays provides an information on mass of strange quark and $|V_{us}|$ element of CKM matrix. The 5-prong tau decays are studied with large statistics and not observed 7-prong decays are used to probe non-SM contributions.

A. Non-strange spectral function

The calculation of hadronic part of the anomalous magnetic moment of muon $a_\mu^{had,LO}$ includes integral of the cross-section $e^+e^- \rightarrow \text{hadrons}$ multiplied with QED kernel $K(s)$. The structure of $K(s)$ is such, that 75% of $a_\mu^{had,LO}$ is covered by two pion final state dominated by $\rho(770)$ resonance. Assuming isospin invariance, $\sigma(e^+e^- \rightarrow \pi^+\pi^-)$ can be estimated from the branching fraction $B(\tau^- \rightarrow \pi^- \pi^0 \nu)$ [10]. Currently, the results based on tau data together with results of Muon g-2 experiment[4] give $a_\mu^{exp} - a_\mu^{SM} = (9.4 \pm 10.5) \cdot 10^{-10}$, while calculation based solely on e^+e^- data is $a_\mu^{exp} - a_\mu^{SM} = (25.2 \pm 9.2) \cdot 10^{-10}$ [10]. Belle has recently presented new preliminary study of $\tau \rightarrow \pi \pi^0 \nu$ decay[11]. The measured $\pi^- \pi^0$ invariant mass spectrum is corrected for the detector deficiency and distortions

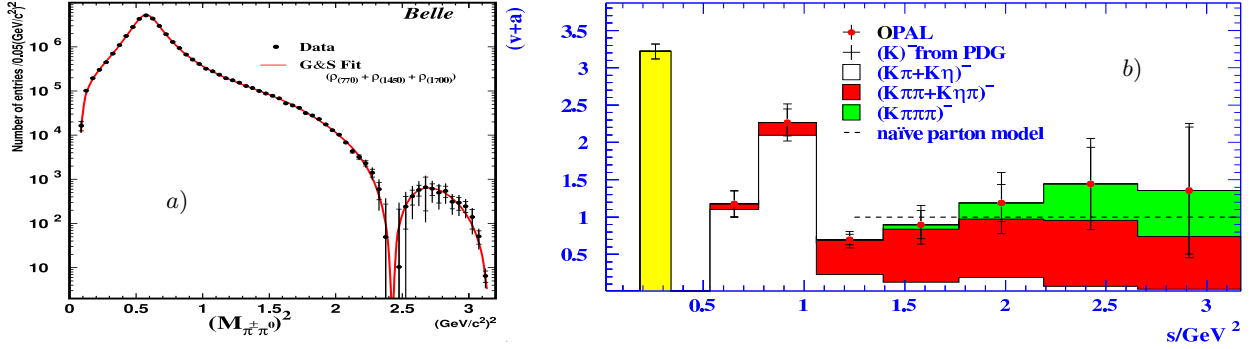


FIG. 1: a) Fully corrected $m_{\pi\pi^0}^2$ distribution for $\tau \rightarrow \pi\pi^0\nu$. The solid curve is the result of a fit to the Gounaris-Sakurai model with $\rho(770)$, $\rho'(1450)$ and $\rho''(1770)$ resonances. b) The spectral function from strange tau decays. The dots show the inclusive spectrum as measured in OPAL[13]. The histograms show exclusive spectra as described on the plot.

using the unfolding technique and then fitted with Gounaris-Sakurai function as shown on Fig. 1a. The distribution also exposes ρ'' resonance, evident in this decay for the first time. The obtained $\pi\pi$ contribution to a_μ is $a_\mu^{\pi\pi} = (462.4 \pm 0.6_{stat} \pm 3.2_{sys} \pm 2.3_{isospin}) \cdot 10^{-10}$, which yields $a_\mu^{exp} - a_\mu^{SM} = (11.0 \pm 10.5) \cdot 10^{-10}$, in good agreement with ALEPH and CLEO data. Although, only 72 fb^{-1} were used in this analysis, the systematic uncertainties, such as on the track and π^0 reconstruction efficiency, dominate and it is unlikely to be improved with larger statistics.

B. Strange spectral function

Analysis of strange tau decays allows to extract mass of strange quark m_s and $|V_{us}|$ element of CKM matrix via moments of the strange spectral function (SSF):

$$R_\tau^{kl} = \int_0^{M_\tau^2} ds \left(1 - \frac{s}{m_\tau^2}\right)^k \left(\frac{s}{m_\tau^2}\right)^l \frac{B(\tau \rightarrow X^{(S=-1)}\nu)}{B(\tau \rightarrow e\nu\nu)} \frac{dN_{X^{(S=-1)}}}{N_{X^{(S=-1)}} ds}. \quad (3)$$

R_τ^{kl} are calculable within operator product expansion framework with phenomenological hadronic parametrization[12].

The $R_\tau^{(0,0)}$ moment is most sensitive to the $|V_{us}|$, while its dependence on m_s is small and can be neglected[12]. This allows to extract $|V_{us}| = 0.2208 \pm 0.0033_{exp} \pm 0.0009_{th}$ from results of OPAL[13] assuming $m_s(2\text{GeV}) = 95 \text{ MeV}$. The value is already very competitive with the estimate from $K \rightarrow \pi e \nu$ decays $|V_{us}| = 0.2200 \pm 0.0026$ [14] and unlike in $K \rightarrow \pi e \nu$ case the theoretical uncertainty is significantly smaller than experimental. Higher order moments are more sensitive to the m_s and one extracts $m_s(2\text{GeV}) = (81 \pm 22) \text{ MeV}$ from the same data. The authors of [12] anticipate simultaneous extraction of m_s and $|V_{us}|$ from the data in future.

The OPAL result is largely statistics limited with total of 162 thousands of identified tau events. While there is only a preliminary result from BaBar on $B(\tau \rightarrow K\pi^0\nu) = (4.38 \pm 0.04_{stat} \pm 0.22_{sys}) \cdot 10^{-3}$ available, one can expect a significant improvement of knowledge of SSF from B-factories. The statistical uncertainties is very small, and systematic uncertainties are largely correlated for different $\tau \rightarrow X^{(S=-1)}\nu$ exclusive channels, and the measurement is expected to be few times more precise than current PDG value of $B(\tau \rightarrow X^{(S=-1)}\nu) = (29.1 \pm 0.8) \cdot 10^{-3}$ [14].

C. 5- and 7-prong tau decays

With such big sample at hand, one can look into underlying structure of rare tau decays. BaBar has recently published a study of 5-prong decays $\tau^- \rightarrow 3h^- 2h^+ \nu$ [15]. The branching fraction is $(8.56 \pm 0.05 \pm 0.42) \cdot 10^{-4}$ in

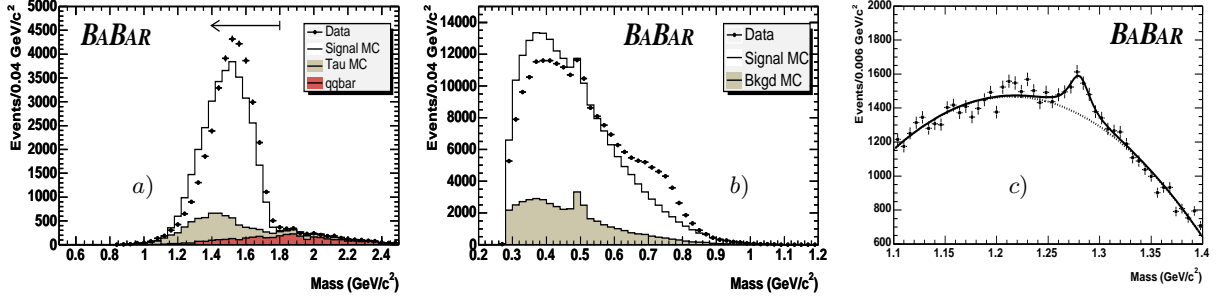


FIG. 2: Invariant mass of a) five charged particles b) h^+h^- pairs c) $2h^+2h^-$ combinations. All tracks are taken as pions. The points are the data and the histograms are the Monte Carlo simulation. The unshaded and shaded histograms are the signal and background events, respectively. The Monte Carlo sample is normalized to the luminosity of the data sample. The solid line on plot c is a fit to the data.

agreement with previous measurements[14]. However, the invariant mass of five hadrons is different from the phase-space distribution assumed before (see Fig. 2). The contribution of ρ meson is evident in the mass of two pion, and f_1 resonance is observed in the four pion mass distribution, $B(\tau^- \rightarrow f_1 h^- \nu_\tau) = (3.9 \pm 0.7 \pm 0.5) \cdot 10^{-4}$ [15]. BaBar has also searched for 7-prong tau decays. If observed, they would signal of non-SM contribution, as SM predicts $B(\tau^- \rightarrow 4\pi^- 3\pi^+ \nu) < 10^{-9}$. No signal is found in either exclusive or inclusive 7-prong tau decays and the obtained upper limits are

$$\begin{aligned} B(\tau^- \rightarrow 4\pi^- 3\pi^+ (\pi^0) \nu_\tau) &< 3.0 \cdot 10^{-7} \\ B(\tau^- \rightarrow 4\pi^- 3\pi^+ \nu_\tau) &< 4.3 \cdot 10^{-7} \\ B(\tau^- \rightarrow 4\pi^- 3\pi^+ \pi^0 \nu_\tau) &< 2.5 \cdot 10^{-7} \end{aligned} \quad (4)$$

at 90% CL[16]. 232 fb^{-1} is used in both analyzes.

IV. SEARCHES FOR LEPTON FLAVOR VIOLATION

One of the most interesting question in tau physics now is there a sizable lepton flavor violation (LFV) or not. Given the observation of neutrino oscillation by experiment[17], one expects charged LFV even in Standard Model extended with massive neutrinos. However, the expected branching fractions are negligible and far beyond reach of the current experiments. From other side, many other extensions of SM, e.g. supersymmetry, predict LFV on the level of $10^{-10} - 10^{-7}$ [18], which can be probed with currently accumulated statistics. Analysis of different channels is important. While $\tau \rightarrow \mu\gamma$ is expected to be the largest tau LFV decay in most models, $\tau \rightarrow 3\ell$ can expose supersymmetric Higgs contribution[19], and $\tau^- \rightarrow \ell^+ h^- h^-$ violates not only lepton flavor, but also lepton number. If LFV process would be observed in an experiment, the combined analysis of different channels will allow to understand underlying mechanism and to differentiate between the models.

Both BaBar and Belle are very active in searches of lepton flavor violation. Unfortunately, no signal is found in any channel and upper limits are set on the level of 10^{-7} (see table I). Both experiments plan to increase their samples by factor of 2 by 2008.

The obtained limits can already be used to restrict parameter space of the models. The Fig 3a[21] shows the exclusion plot for mSUGRA with right handed neutrinos as function of gaugino ($m_{1/2}$) and scalar (m_0) masses at grand unification scale $m_{GUT} = 5 \cdot 10^{15} \text{ GeV}$ for $\tan\beta = 50$. The latest measurements of neutrino mixing matrix and masses[22] are used for Yukawa couplings. The mass of right handed neutrinos is set to $M_{\nu_R} = 5 \cdot 10^{14}$ and normal hierarchy is assumed for left handed neutrinos. Everything but a green area is excluded by theory or cold

TABLE I: 90% CL upper limits on LFV tau decays obtained by B-factories[20]. Numbers given in 10^{-7} units. Second column for each experiment shows integrated luminosity used in analysis.

	BaBar		Belle	
Channel	UL	\mathcal{L}	UL	\mathcal{L}
$\tau^- \rightarrow \mu^- \gamma$	0.7	232 fb $^{-1}$	3.1	86 fb $^{-1}$
$\tau^- \rightarrow e^- \gamma$	1.1	232 fb $^{-1}$	3.9	87 fb $^{-1}$
$\tau^- \rightarrow e^- e^+ e^-$	2.0	91 fb $^{-1}$	3.5	87 fb $^{-1}$
$\tau^- \rightarrow \mu^- \mu^+ \mu^-$	1.9	91 fb $^{-1}$	2.0	87 fb $^{-1}$
$\tau^- \rightarrow \ell^- \ell^\pm \ell'^\mp$	(1-3)	91 fb $^{-1}$	(2-4)	87 fb $^{-1}$
$\tau^- \rightarrow \ell^- h^+ h^-$	(1-3)	221 fb $^{-1}$		
$\tau^- \rightarrow \ell^+ h^- h^-$	(0.7-5)	221 fb $^{-1}$		
$\tau^- \rightarrow \ell^- \pi^0, \eta, \eta'$			2-10	154 fb $^{-1}$
$\tau^- \rightarrow \Lambda \pi^-$			0.7	154 fb $^{-1}$
$\tau^- \rightarrow \bar{\Lambda} \pi^-$			1.4	154 fb $^{-1}$

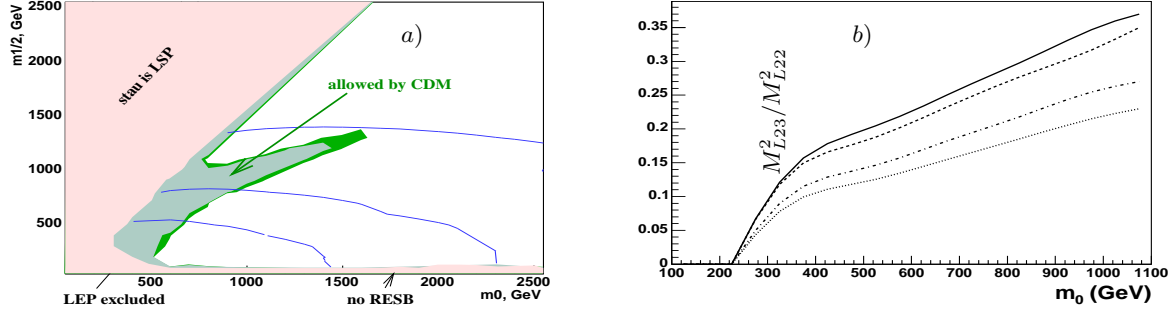


FIG. 3: a) Exclusion plot of $mSUGRA$ with right handed neutrinos as function of gaugino ($m_{1/2}$) and scalar (m_0) masses for $\tan\beta = 50$. The green area is allowed by cold dark matter searches and blue curves show area excluded by $\tau \rightarrow \mu\gamma$ as described in the text. b) Model independent upper limits of off-diagonal element of slepton mixing matrix M_{L23}^2/M_{L22}^2 as function of m_0 from $B(\tau \rightarrow \mu\gamma)$ as described in the text.

dark matter density measurement, while the area below blue curves (towards center of coordinates) is excluded by tau LFV searches. The blue curves from center of coordinates onwards correspond to the $6.8 \cdot 10^{-8}$, $1 \cdot 10^{-8}$ and $1 \cdot 10^{-9}$. One can expect that by 2008 the combined sensitivity of BaBar and Belle will reach $1 \cdot 10^{-8}$ level, while running super- B factory will be necessary to reach $1 \cdot 10^{-9}$ level.

Figure 3b[21] shows the upper limits set on off-diagonal elements of slepton mixing matrix M_{L23}^2/M_{L22}^2 (model independent approach) as function of m_0 for $\tan\beta = 50$ and $m_{1/2} = 100 + 0.8 \cdot m_0$. The uppermost curve corresponds to $6.8 \cdot 10^{-8}$, followed by curves of $5 \cdot 10^{-8}$, $2 \cdot 10^{-8}$ and $1 \cdot 10^{-8}$.

V. CONCLUSIONS

Current B -factories have a large and interesting program to study tau physics. The accumulated statistics reaches 10^9 tau decays which allows very precise measurements and searches of very rare or forbidden tau decays. Among the most important measurements are mass and tau lifetime (systematics limited) and tests of CPT/CP violation (statistics limited). The study of the spectral function of $\tau \rightarrow \pi\pi^0\nu$ decay would help to clarify the comparison of measurement of anomalous magnetic moment of muon with its SM prediction, while strange spectral functions are to

be used for m_s and $|V_{us}|$ estimates.

Among very interesting studies are searches of lepton flavor violation tau decays. While BaBar and Belle can be lucky to discover LFV and this way to probe the physics beyond Standard Model, one would need statistics of super- B factory to be able to measure mixing of sleptons accurately.

-
- [1] B. Aubert *et al.* [BABAR Coll.], Nucl. Instrum. Meth. A **479**, 1 (2002)
 - [2] A. Abashian *et al.* [BELLE Coll.], Nucl. Instrum. Meth. A **479**, 117 (2002).
 - [3] J. Z. Bai *et al.* [BES Coll.], Phys. Rev. D **53**, 20 (1996).
 - [4] G. W. Bennett *et al.* [Muon g-2 Coll.], Phys. Rev. Lett. **89**, 101804 (2002)
 - [5] K. Abe *et al.* [BELLE Coll.], arXiv:hep-ex/0511038.
 - [6] H. Albrecht *et al.* [ARGUS Coll.], Phys. Lett. B **292**, 221 (1992).
 - [7] A. Lusiani *et al.* [BABAR Coll.], Nucl. Phys. Proc. Suppl. **144**, 105 (2005).
 - [8] G. Bonvicini *et al.* [CLEO Coll.], Phys. Rev. Lett. **88**, 111803 (2002)
 - [9] P. Avery *et al.* [CLEO Coll.], Phys. Rev. D **64**, 092005 (2001)
 - [10] M. Davier *et al.*, Eur. Phys. J. C **27**, 497 (2003)
 - [11] K. Abe *et al.* [BELLE Coll.], arXiv:hep-ex/0512071
 - [12] E. Gamiz *et al.*, Nucl. Phys. Proc. Suppl. **144**, 59 (2005)
 - [13] G. Abbiendi *et al.* [OPAL Coll.], Eur. Phys. J. C **35**, 437 (2004)
 - [14] S. Eidelman *et al.*, Phys. Lett. B **592**, 1 (2004)
 - [15] B. Aubert *et al.* [BABAR Coll.s], Phys. Rev. D **72**, 072001 (2005)
 - [16] B. Aubert *et al.* [BABAR Coll.], Phys. Rev. D **72**, 012003 (2005)
 - [17] K. Eguchi *et al.* [KamLAND Coll.], Phys. Rev. Lett. **90**, 021802 (2003); Q. R. Ahmad *et al.* [SNO Coll.], Phys. Rev. Lett. **89**, 011301 (2002); Y. Fukuda *et al.* [Super-Kamiokande Coll.], Phys. Rev. Lett. **81**, 1562 (1998)
 - [18] E. Ma, Nucl. Phys. Proc. Suppl. **123**, 125 (2003)
 - [19] K. S. Babu and C. Kolda, Phys. Rev. Lett. **89**, 241802 (2002)
 - [20] B. Aubert *et al.* [BABAR Coll.], Phys. Rev. Lett. **95**, 041802 (2005); Phys. Rev. Lett. **96**, 041801 (2006) Phys. Rev. Lett. **92**, 121801 (2004); Phys. Rev. Lett. **95**, 191801 (2005)
K. Abe *et al.* [BELLE Coll.], Phys. Rev. Lett. **92**, 171802 (2004); K. Hayasaka *et al.*, Phys. Lett. B **613**, 20 (2005); Y. Yusa *et al.* [BELLE Coll.], Phys. Lett. B **589**, 103 (2004); arXiv:hep-ex/0603036. Y. Enari *et al.* [BELLE Coll.], Phys. Lett. B **622**, 218 (2005) Y. Miyazaki *et al.* [BELLE Coll.], Phys. Lett. B **632**, 51 (2006);
 - [21] O. Igonkina, The 13th International Conference on Supersymmetry and Unification of Fundamental Interactions, (Durham, UK), Jul 18-23, 2005
 - [22] M. C. Gonzalez-Garcia, arXiv:hep-ph/0410030